Decision Criteria for the Rehabilitation of Concrete Bridge Decks

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ABSTRACT

Bridge deck rehabilitation is consuming an increasing proportion of the resources of highway agencies. The nature and extent of deterioration is highly variable such that there is neither a single problem of bridge deck durability nor a single solution.

The paper presents a systematic approach to bridge deck rehabilitation. The requirements for a condition survey are described. The performance of concrete overlays, waterproofing membranes and cathodic protection applied to existing structures is assessed from field studies and literature. Decision criteria which can be used to identify the most appropriate method of rehabilitation for any particular structure are given.

INTRODUCTION

An increasing emphasis is being placed on the maintenance and rehabilitation of bridges. Many structures which in the past were replaced as part of improvements in the alignment of a highway must now be kept in service as fewer changes are being made in the highway network. Deterioration is especially serious in bridge decks in areas of North America where deicing chemicals are used in winter maintenance operations. The salt penetrates the concrete and initiates corrosion of the steel reinforcement. This in turn causes cracking and rupturing of the concrete and spalling of the concrete surface. In addition, some older bridge decks, built to lower standards of quality than modern structures and constructed without the benefits of efficient waterproofing systems and air entrainment, suffer a more deep seated distress as the concrete progressively disintegrates from the surface downwards under freeze-thaw action.

A major consideration which complicates the development of a policy for bridge deck rehabilitation is the inherent variability in the condition of the structural concrete, the reinforcing steel (and, more recently the prestressing systems) in the structures under the jurisdiction of any single authority. Such variability is inevitable because the condition of the deck slab is influenced by many factors, the most important being age, the standards in use at the time of construction, the quality of the materials and workmanship, the type of design and the service environment. Since it is clear that no single problem of bridge deck durability exists, it is also apparent that there is no single solution for the rehabilitation of all

concrete deck slabs. What is needed is a systematic approach which includes the identification of the deterioration on a particular structure and the development of decision criteria which lead to the selection of the most cost-effective solution for that structure.

CONDITION SURVEYS

A condition survey of a bridge deck may be required for either of the two reasons. Firstly, to establish repair priorities on a state-wide scale and secondly, to provide details of the nature and extent of concrete deterioration needed for design and execution of the restoration work.

The work required to determine repair priorities can be described as a general survey and the more comprehensive inspection prior to the design of the restoration work is called a detailed condition survey.

The objective of the general survey is to obtain an overall rating of the deck slab so that where necessary it can be programmed for restoration at some future date. Deck slabs with an exposed concrete surface are relatively straightforward to rate and measurements of concrete cover, half cell potentials of the reinforcing bars, areas of temporary patches and delaminations, presence of significant cracks and scaled areas on a sample area of the concrete surface provide adequate information in most cases.

The presence of an asphalt wearing surface on a bridge deck, which is the case for the majority of structures in Ontario,

makes it difficult to determine the overall condition of the concrete slab. Some asphalt covered deck slabs date back to the 1920's and their condition is highly variable (1). Where a more advanced stage of deterioration is present it is sometimes obvious from a visual examination of the deck, and programing of the rehabilitation work can proceed without the necessity of a general survey. In most cases, however, it will be necessary to take core samples and remove small sections of the asphalt overlay to ascertain the condition of the concrete. Some general criteria can also be established that will assist in determining whether deterioration is likely and a general survey of the structure is required. The age of the structure is a key indicator of its condition. Cracking and repairs to the asphalt, or leakage, wet spots or cracks on the underside of the deck slab are useful clues to the condition of the concrete in the deck. Severe deterioration of exposed concrete such as sidewalks, curbs and handrail posts may also be indicative of deterioration in the deck slab.

Detailed condition surveys are carried out when the structure has been programed for rehabilitation and it is necessary to select the method of repair and prepare the contract documents. Although guidelines and the general scope of the survey can be prepared in advance, the details of the work must be determined by the Engineer on site. Factors to be considered include existing information of the condition of the deck slab and additional information to be gained as the work proceeds. For example, if it is clear that the deck must be replaced, such as would be the case in an older deck exhibiting widespread

cracking as the result of alkali-aggregate reactivity, then little or no testing is required. Where it is not clear if the deck slab can be effectively rehabilitated or must be replaced, a very detailed survey may be needed.

As with the general survey, asphalt covered decks are more difficult to evaluate than decks with an exposed concrete surface and consequently the cost of the detailed condition survey will be greater and the reliability of the data lower.

In most cases the detailed condition survey will include:

(i) Determination of the condition of the bituminous overlay where present, its thickness and the recording of significant cracks in the wearing surface.

(ii) Appraisal of the condition and identification of the type of the waterproofing membrane where present.

(iii) Recording and measurement of patched and open spalled areas, delaminated concrete, scaled areas, and significant cracks on exposed concrete deck surfaces.

(iv) Survey of concrete cover to top layer of reinforcing steel. On asphalt covered decks, cover can only be measured where sections of the asphalt overlay are removed.

(v) Determination of corrosion activity of the top layer of reinforcing steel by measuring half cell potentials. Holes need to be drilled through the bituminous overlay to the deck surface to ensure a good electrical contact.

(vi) Determination of the general condition of the concrete slab by coring and removal of sections of asphalt overlay.

(vii) Tests on concrete core samples to determine chloride content, air void system and occasionally, compressive strength.

(viii) Inspection of the underside of the deck slab and identification of deteriorated concrete, wet areas, efflorescence, significant cracks, corrosion spalling and other defects.

(ix) Inspection of deck drains and identification of condition, position and adequacy.

(x) Inspection of curbs, sidewalks, barrier walls, handrails and other components of the structure above the riding surface.

(xi) Condition, type and measurement of expansion and fixed joint assemblies and special features needed for future reconstruction.

(xii) Identification of other parts of the structure which should be repaired as part of the contract for rehabilitation of the deck.

(xiii) Production of a comprehensive report for the deck slab containing plans, core logs, photographs, tables, and test data that documents in detail the condition of the deck slab and its components.

The methods of test, the number of samples required and the sequence of operations are discussed in detail elsewhere (2).

OPTIONS FOR REPAIR

Many methods of bridge deck rehabilitation have been proposed and investigated. This paper discusses the application of the three methods of rehabilitation which are currently used in Ontario when major rehabilitation of either an exposed concrete or an asphalt covered deck slab is required. The three methods are patching, followed by waterproofing and paving, application of a concrete overlay, and cathodic protection. Temporary repairs such as local patching or epoxy injection are not discussed.

Although it is not the intention to describe in detail the construction procedures involved in each method since these are well documented elsewhere (2, 3, 4), the essential processes of each method are as follows:

Patching, waterproofing and paving consists of saw-cutting around areas of delaminated and spalled concrete, removing all unsound concrete, patching (usually with portland cement concrete), application of a waterproofing membrane, a protective layer and a bituminous wearing course. Although there is a multitude of waterproofing systems available, those which have proven most satisfactory, all require application of a protection board and bituminous concrete (5).

The placing of a concrete overlay consists of scarifying the entire deck surface, removal of all delaminated and unsound concrete, application of a bonding layer followed by an overlay which may consist of high quality conventional portland cement concrete or a latex modified concrete.

The installation of the type of cathodic protection system used in Ontario (4) consists of placing concrete patches in exactly the same manner as if the deck were to be waterproofed, placing anodes in the deck surface and the application of an electrically conductive bituminous mixture and a conventional bituminous wearing course. Power, in the form of a low voltage direct current, is supplied to the anodes from an alternating current rectifier.

On bridge decks where corrosion of the reinforcing bars and shallow surface spalling is the basic problem, one of the most difficult decisions to make is to define the amount of concrete which must be removed as part of the repair contract. The chloride ion concentration in most bridge decks in need of repair exceeds the threshold value sufficient to initiate corrosion of the reinforcing steel. The threshold value is commonly accepted to be 0.15% of the soluble chloride by mass of cement content of the concrete (6). Under these circumstances, unless cathodic protection is to be applied, the only method to ensure that corrosion does not continue is to remove all the concrete containing chlorides in excess of the threshold value and then prevent further applications of deicing salts from gaining access to the reinforcing steel (7, 8). Most of the chloride contaminated concrete is, however, usually physically sound such that its removal is not only tedious but very expensive and the cost of its removal may approach that of deck replacement. Deck replacement except where required for structural reasons, or the removal of all the chloride contaminated concrete are beyond the financial resources of most highway authorities. Consequently, many authorities believe it is more

economical not to remove chloride contaminated concrete which is otherwise sound and to accept the risk arising from the uncertainty surrounding the future life of the deck slab. This practice which is termed "experimental cost effective reconstruction" is common in both the United States (9) and Canada (3).

PERFORMANCE OF REHABILITATION METHODS

The effect of waterproofing or a concrete overlay on the continuing corrosion activity in a bridge deck is not well documented and yet the ability to predict the future life of the deck slab is an essential ingredient in the technical and financial analysis which must be undertaken to select the most appropriate repair method. Data upon which investment decisions can be made is lacking because not only is major deck rehabilitation a relatively new phenomenon but many of the methods have only been in use for a few years and satisfactory tools for measuring the performance of rehabilitation schemes have generally not been available. The use of the half cell method of measuring the corrosion activity of the reinforcing steel in a concrete bridge deck was first reported in 1973 (10) and formalized as a standard method of test in 1977 (11). It is only recently that systematic surveys to document the condition of decks prior to repair and to monitor their performance after repair have been initiated by highway agencies. Few results have yet been published because of the number of years required to establish meaningful trends.

CONCRETE OVERLAYS

The first low slump concrete overlay in Ontario was placed in May, 1976 and has been monitored regularly. The results of the

annual half cell surveys are shown in Figure 1. The results are presented in the form of cumulative frequency distribution curves which is a convenient method of observing changes in corrosion activity between surveys. Using this method of presentation a shift of the curve to the left indicates a reduction in corrosion activity and vice versa. The significant reduction in corrosion activity immediately following application of the concrete overlay has previously been reported (3). This occurs because concrete is removed from around the bars exhibiting the greatest corrosion activity. Delaminations are usually associated with a half cell potential of more (negative) than -0.50 v and in the course of removing delaminated concrete it is often necessary to remove the concrete from around the exposed bars. In placing the concrete overlay these exposed bars are covered by the mortar bonding grout and are surrounded by chloride-free concrete, with the result that corrosion activity is suppressed in these areas. Later measurements have shown that the initial reduction in corrosion activity has not been sustained and the overall level of activity has gradually increased. Although Figure 1 shows the results of the 1978 to the right of the curve representing the original deck survey, the area of the deck exhibiting active corrosion (more negative than -0.35 v) is less than it was before applying the overlay and the highest potential recorded is much less than the pre-overlay condition.

The results of the half cell surveys on a badly deteriorated deck which received a low slump concrete overlay in 1977 are shown in Figure 2.

Two surveys prior to overlay are shown and the measurements demonstrate the significant increase in corrosion activity which occurred between 1976 and 1977. Figure 2 also shows the sharp reduction in corrosion activity following construction of the overlay noted in Figure 1 but the increase in the second year was only slight. The deck represented in Figure 2 was considerably more deteriorated than that represented in Figure 1 so that a greater portion of the reinforcing steel was surrounded by new concrete. This may account for the slower rate of increase in corrosion activity.

Other decks which have received either a low slump or a latex modified concrete overlay have been monitored and found to exhibit similar trends to those illustrated in Figures 1 and 2 which can be considered to represent the range of the conditions recorded. Other authorities have reported a similar initial reduction in corrosion activity beneath low slump concrete overlays (12, 13) and latex modified concrete overlays (14, 15) but this has not always been the case. On some structures corrosion activity has continued (16) or increased (12) following placement of a latex modified concrete overlay. The wider variation in the results with the latex modified concrete overlays is probably the result of wetting down the deck which is necessary prior to applying the latex modified bonding grout. Rapid rust formation takes place when exposed reinforcing bars, which have been sandblasted, are wet down and this may mask the overall change in the corrosion activity of the reinforcing steel.

Although the determination of half cell potentials is a valid measure of the presence of corrosion activity in a bridge deck, it does not measure the rate of corrosion, which is determined primarily by the availability of oxygen and moisture at the cathode and the structure and formation of the corrosion products at the anode. It is possible to have a high corrosion potential reading but a very low rate of corrosion such that physical distress may not occur for many years, and similarly rapid corrosion rates may be associated with lower, but active, potential readings. Consequently, the corrosion potentials are a useful indication of performance but the deciding factor will always be actual service life in the field.

Concrete overlays have been used in many jurisdictions including British Columbia (17) and several State highway departments for up to 15 years. A report published by Iowa State Highway Commission in 1974 (18) indicated good performance of overlays which were then one to nine years old, despite relatively high chloride levels in the concrete in the original deck slab. A more recent study (19) reports the investigation of the condition of the same bridge decks five years after the original investigation. The latest study included a delamination survey and the measurement of corrosion potentials which were not part of the original survey. The results show that the majority of the decks exhibited delaminations, most of which were just below the bond line between the overlay and the original deck concrete. Despite the presence of the delaminations, no surface distress was observed and the performance of overlays on chloride contaminated decks was considered adequate. It should be noted

that the overlays were constructed to specifications which required thinner overlays and the removal of less concrete than existing specifications.

A survey of 149 latex modified concrete overlays in Ohio, West Virginia, Michigan and Kentucky (14), some of which were more than 15 years old, found that, despite local debonding and cracking, performance was generally satisfactory. Consequently, the trends in the corrosion potentials reported in Figure 1, and the performance of overlays in Iowa and elsewhere, give a better indication of the economic life of a concrete overlay applied to a chloride contaminated deck that has previously been possible and suggest that 15 to 20 years is probably realistic.

PATCH, WATERPROOF AND PAVE

Data to indicate the effect of repairing a chloride contaminated deck by patching, waterproofing and paving is even less available than for concrete overlays. In Ontario, systematic "before and after" surveys have not been made but in 1978 a study was undertaken to determine the effect of waterproofing on the corrosion activity in a deck slab. Where half cell readings had been taken on deck slabs which had subsequently been waterproofed, potentials were measured at the same grid points by drilling through the waterproofing to ensure an electrical contact with the deck surface. For most structures only part of a deck was included in the original survey, in which case only the same part of the structure was included in the 1978 survey.

The most reliable data was available from two structures which were built in 1959 and 1960 with a bituminous concrete surface but without a waterproofing layer. The concrete decks were exposed in 1975 and resurfaced with a hot applied rubberized asphalt waterproofing membrane, a protection board and 75 mm (3 in.) of hot mix as part of the same resurfacing contract. Half cell measurements, cover and areas of delamination were recorded on both decks when they were exposed in 1975. The half cell data, together with that from the 1978 survey, is shown for each structure in Figures 3 and 4.

When the Nith River bridge was examined in 1975, extensive areas of delamination were recorded, these being associated with areas of inadequate cover to the reinforcing steel. The cover varied between 20 mm (0.75 in.) and 60 mm (2.375 in.) with an average of 35 mm (1.38 in.). Delaminated concrete was removed and concrete patches were placed in the spalled and delaminated areas. The deck on the CPR structure was in good condition in 1975 and free from delamination. The cover varied between two isolated readings of 25 mm (1 in.) and a high of 70 mm (2.75 in.) with an average of 55 mm (2.2 in.).

Seven cores were taken in 1978 from the Nith River Bridge, five of which were taken at grid points included in the 1975 survey. The half cell potential measurements at the time of the two surveys and the condition of the cores are given in Table 1. Of the five cores which were taken where the potential was -0.50 v or greater, three were found to be delaminated. Although it is possible that not all delaminated areas were

removed at the time of repair in 1975, it is unlikely, and the half cell measurements taken at the location of core numbers 4 and 6 in 1975 suggest that the delaminations were not present at the time the waterproofing was applied. Figure 3 also shows that there has been an increase in the overall corrosion activity in the deck between the time it was waterproofed and examined three years later.

The opposite effect has occurred on the CPR structure where there has been a reduction in corrosion activity since the deck was waterproofed. An attempt was made to compare the effectiveness of the waterproof membrane on the two decks by resistivity measurements (20). The resistivity on both decks was low although this is thought to be the result of moisture in the bituminous concrete shorting the electrical circuit to the reinforcing steel by way of the deck drains. In selected locations on both decks the waterproofing was examined by removing the bituminous concrete. In all cases it was found to be well bonded to both the deck and the protection board, of uniform thickness and in good condition. The reasons for the difference in performance of the waterproofing membranes is not clear.

Wide variations in the performance of waterproofing membranes applied to chloride contaminated decks have been the common denominator in other bridge deck surveys. A survey of 74 structures was undertaken in Ontario in 1974 to evaluate the effectiveness of waterproofing membranes (21) and both electrical resistivity and half cell potential measurements were made.

Thirty-seven of the structures tested exhibited active corrosion potentials including some of the seventeen structures which were new at the time of waterproofing. There was no correlation between the resistivity and the corrosion measurements such that high resistivity readings, indicating good membrane performance, were often associated with high potential measurements. A similar lack of correlation between resistivity and corrosion was found in a survey of 44 decks in New York State (22). All the decks were waterproofed after being in service for a number of years. Forty percent of the decks indicated active corrosion over greater than 25% of the deck area. Where half cell measurements were made on the same deck over a number of years the number of readings in excess of -0.35 v fluctuated widely from year to year. With few exceptions, the percentage of readings indicating active corrosion increased with time. Work in California has shown that repair of delaminations prior to waterproofing will reduce the percentage of active corrosion potentials on a deck but that corrosion activity will continue at other locations in a chloride contaminated deck (23). Other surveys in the United States have reported both a reduction in corrosion activity (12) and renewed spalling (24) beneath membranes applied to decks previously exposed to deicing salts.

In many ways the results of the surveys in waterproofed decks are confusing and the effect of waterproofing on the future service life of the deck slab is unpredictable. Spalls and delaminations have occurred with three years of waterproofing a chloride contaminated deck and, given the variability in

membrane performance, it would seem prudent to seek other methods of rehabilitating such decks until such time as the effect of the waterproofing is better understood.

CATHODIC PROTECTION

Cathodic protection differs from the application of a waterproofing membrane or a concrete overlay in that it actively prevents continued corrosion of the reinforcing steel. The low voltage direct current which is applied over the deck surface by way of the conductive mixture polarizes the reinforcing steel so that corroding anodes on the steel are prevented from discharging ions and become current receiving cathodes. The effectiveness of the cathodic protection in arresting the corrosion of the reinforcing steel has been demonstrated by embedding corrosometer probes in the deck slab (4).

The first installation of cathodic protection on a bridge deck in Ontario took place in 1974 (25). Only half the deck was protected because the method was considered experimental. The remaining half received a dense bituminous concrete overlay and served as the control for the experiment. All spalls on both sides of the deck were patched with concrete and the delaminated areas injected with epoxy.

The bituminous concrete was removed in 1977 so that the concrete deck slab could be examined and a cathodic protection system applied to the entire deck. Numerous delaminations were located on the unprotected side of the deck.

Delaminations were also located on the protected side of the deck although closer examination showed that these could be divided into two categories: those which had occurred in areas previously injected with epoxy and those which were adjacent to the centreline of the deck. The epoxy used to inject the delaminated areas in 1974 was a dielectric material which prevented the flow of current to the reinforcing steel beneath the injected areas and further corrosion took place. The delaminations adjacent to the centreline were part of much larger delaminations on the unprotected north side and the extension of the delaminations into the south side was thought to be the result of corrosion activity in the unprotected side (27).

The examination of the deck surface confirmed the effectiveness of cathodic protection in arresting corrosion in a deck slab but also resulted in a change in repair practices. These now require the removal of all delaminated areas and the placing of concrete patches prior to applying cathodic protection. Newer installations have also included the recessing of the electrical hardware and the use of a conductive mixture with good stability characteristics (26).

FACTORS INFLUENCING THE SELECTION OF THE REPAIR METHOD

The selection of the most appropriate method of repair for any particular structure is determined not only by the technical considerations which have already been discussed but by numerous other factors, some of which are economic and others which are purely practical.

Although the purpose of this paper is to present a systematic approach to bridge deck rehabilitation, repairs to the deck cannot be separated from an evaluation of the condition and load-carrying capacity of the remainder of the structure. If the structure as a whole is found to be functionally obsolete when current criteria for width, clearances, alignment and load limits are applied, or if deficiencies are noted in other components of the structure which will limit its service life, then the deck rehabilitation strategy must be compatible with the life of the structure as a whole. Methods of conducting an economic analysis to determine the cost benefit of replacing or repairing a structure and for establishing repair priorities between structures have been published (28, 29, 30) but the usefulness of the analysis is limited by the accuracy with which the cost and the life expectancy of the various rehabilitation schemes can be predicted.

The factors which influence the selection of the repair method and the priority for repair can be summarized as follows:

1. The location of the structure and its importance in the highway network.
2. The volume of traffic at the site and the impact of lane closures on traffic flow.
3. The type of structure, its size and geometry.
4. The nature of the deterioration.
5. The extent of the deterioration.
6. The anticipated service life of the structure.
7. The load-carrying capacity of the structure.

8. The cost of repairs and the availability of funds.
9. The future reconstruction program.
10. Local experience and contractor expertise.

The importance of a structure is determined by traffic volumes at the site and the availability of alternate routes. Consequently, some freeway structures warrant a greater priority for repairs and a higher standard of maintenance than could be justified for other structures in the highway network. Traffic volumes also influence the choice of the method of repair in that they determine the number of lanes which can be closed at any one time and in some cases, may dictate the selection of a rehabilitation scheme which is expedient rather than one which is the most technically desirable. Greater priority must also be given to the repair of structures where the deck is part of the main structural member as in the case of thick slab structures and some box and tee girder bridges. The size of the structure influences the economics of the various rehabilitation strategies and unusual deck geometry may eliminate some repair methods. For example, structures with changing superelevation, large skews or sharp tapers may exclude the use of finishing machines having transverse oscillating screeds such as used in placing low slump concrete overlays. Latex modified concrete overlays are difficult to place on steep grades and crossfalls. Similarly, waterproofing membranes should not be used on grades in excess of 4% or in areas subject to rapid acceleration, braking or the turning movements of vehicles. Cathodic protection cannot be used unless electric power can be supplied to the site although experimental solar powered installations are being developed.

The nature and extent of the deterioration have a very significant effect on the selection of the repair method. On severely deteriorated decks, the patching required prior to the installation of a waterproofing membrane or cathodic protection becomes a major item in the repair contract and, where the deterioration has resulted from inadequate cover, the cover is still inadequate after patching. Conversely, concrete overlays are well suited for use on badly deteriorated decks because the areas of concrete removal do not require perimeter sawcutting and the concrete is replaced in the course of applying the concrete overlay. Further, the concrete overlay acts as a structural component of the deck and, where the load-carrying capacity of the structure is a factor, the additional load from the bituminous overlays used with waterproofing and cathodic protection may be unacceptable. Active cracks in the deck slab generally preclude the use of concrete overlays because they are susceptible to reflection cracking which may limit their service life. The quality of the concrete in the deck slab must also be evaluated and, where the use of cathodic protection is contemplated, the air void system needs to be measured using the linear traverse or point count method to ensure that the concrete will remain durable after application of the cathodic protection system. The bituminous overlay is permeable and increased the severity of the service environment of the deck slab by increasing the degree of saturation of the concrete and, where the deck surface was previously exposed concrete, the overlay increases the number of freeze thaw cycles. The relative advantages and disadvantages of the various rehabilitation schemes are presented in summary form in Table 2 (2).

The future reconstruction program also influences the time when repairs are undertaken. It may be more economical to include a structure which does not warrant immediate rehabilitation but is located in close proximity to other structures to be repaired than to award a separate contract at a later date, especially if no other work is planned in that area for several years. Local experience is also an important factor in selecting the repair method. For example, some authorities have reported good success with waterproofing membranes (31) and others (32) have replaced membranes within three years of installation. Consideration should also be given to the expertise of local contractors and the available construction equipment.

The foregoing discussion has dealt with the technical and practical considerations in selecting the method of bridge deck rehabilitation but has made no mention of costs. Costs have always been of paramount importance, but vary so widely that it is difficult to generalize. Actual costs for concrete overlays in Ontario have ranged from $55 to $160 per square metre ($5 to $15 per square foot) of deck area. These costs include all the work associated with the application of the concrete overlay such as deck preparation, modification of deck drains and joints, paving of bridge approaches and traffic protection. Costs for cathodic protection, expressed on the same basis, have ranged between $85 and $145 per square metre ($8 to $13.50 per square foot). The costs for patching, waterproofing and paving are strongly dependent upon the amount of patching required but tend to be somewhat lower than the costs of either a concrete overlay or cathodic protection (33). The costs for all three

repair methods vary not only with such obvious items as size and location of the structures involved, but also with less tangible factors such as scheduling, other types of work included in the contract, and the overall volume of construction work (2). To be meaningful, a cost analysis of the various repair schemes which are technically feasible has to be made for each individual repair contract.

THE SELECTION OF THE REPAIR METHOD

Having completed the bridge deck condition survey, the Engineer must use the results of his survey to select the most appropriate method of repair for that particular structure. A method used in Ontario has been to quantify the information summarized in Table 2 and to express it in the form of the decision matrix contained in Table 3. This method has proven very useful provided that one remains cognizant of the other factors discussed in the previous section. The criteria which have been used in constructing Table 3 are based on the experience in Ontario to date but are subject to change as more information on performance, costs and construction experience becomes available.

It should be noted that the decision matrix is constructed such that, by elimination, it leads to the identification of the rehabilitation scheme which is least objectionable rather than identifying the most suitable. This is not accidental; it is an acknowledgement that there is rarely an ideal solution and that the method of repair will always be a compromise between what is technically feasible and economically viable.

In some cases, the matrix may exclude all the methods of repair, as for example a deck with active cracks and with spalls and delamination over more than 5% of the deck area. In this case, it is useful to work through the matrix again and, on the basis of engineering judgement and cost estimates, examine the implications of violating each criterion in turn. In the example quoted the choice may well be between paying the high cost of patching the deck prior to the application of cathodic protection, or accepting the risk of limited service as the result of cracking in a concrete overlay. In extreme cases deck replacement may be the most economical solution. Alternatively, it may be possible to combine more than one system. For example, instead of patching the deck in the example quoted, it may be possible to extend the service life of the deck by applying a concrete overlay followed by either waterproofing and paving or cathodic protection.

CONCLUSION

Bridge deck rehabilitation is both complex and challenging. Decisions often have to be made on the basis of inadequate performance data and in the face of serious operational and financial restraints. Sophisticated methods of analysis are not sufficient: sound engineering judgement, an appreciation of all the factors involved and a systematic approach are the key elements in identifying the most appropriate method of rehabilitating any particular structure. The arbitrary selection of repair method, often made without visiting the structure, can no longer be tolerated. The condition and performance of structures is so highly variable that an individually engineered

solution is required for every structure. This can only be done by completing a detailed condition survey and assessing the implications of the condition of the structure on the cost of repairs and future performance of the bridge deck for the various alternative rehabilitation methods.

REFERENCES

1. Armstrong, M.D. and Wawrzynski, J., "The Condition of Concrete Bridge Decks in Ontario", Proceedings of the Forty-Fourth Convention of the Canadian Good Roads Association, 1963 pp. 142-154.

2. "Durability of Concrete Bridge Decks", NCHRP Synthesis of Highway Practice 57, 1979, 61 pp.

3. Manning, D.G. and Owens, M.J., "Ontario's Experience With Concrete Overlays for Bridge Decks", RTAC Forum, Vol. 2, No. 1, 1979, pp. 31-37.

4. Fromm, H.J. "Cathodic Protection of Rebar in Concrete Bridge Decks" Materials Performance, Vol. 16, No. 11, 1977, pp. 21-29.

5. Van Til, C.J., Carr, B.J. and Vallerga, B.A., "Waterproof Membranes for Protection of Concrete Bridge Decks", NCHRP Report 165, 1976, 70 pp.

6. Clear, K.C. "F.C.P. Annual Progress Report - Year Ending September 30, 1978, Project 4B", Federal Highway Administration, 1978.

7. Clear, K.C., "Evaluation of Portland Cement Concrete for Permanent Bridge Deck Repair", Report No. FHWA-RD-74-5., Federal Highway Administration, 1974, 44 pp.

8. Stewart, C.F., "Considerations for Repairing Salt Damaged Bridge Decks", Journal of the American Concrete Institute, Vol. 72, 1975, pp. 685-690.

9. Federal-Aid Highway Program Manual, Vol. 6, Ch. 7, Sec. 2, Subsec. 7, Transmittal 188, Federal Highway Administration, 1976.

10. Stratfull, R.F., "Half Cell Potentials and the Corrosion of Steel in Concrete", Highway Research Record No. 433, 1973, pp. 12-21.

11. "Standard Test Method for Half Cell Potentials of Reinforcing Steel in Concrete", ANSI/ASTM C876-77, American Society for Testing and Materials, Philadelphia, 1978.

12. Tracy, R.G., "Bridge Deck Deterioration and Restoration", Investigation No. 639, Interim Report II, Minnesota Department of Transportation, 1977.

13. Brown, R.A., "Monolithic Bridge Deck Experimental Cost Effective Restoration, Washington Ave. over I-90", Initial Report, New York State Department of Transportation, 1978.

14. Bishara, A.G., "Latex Modified Concrete Bridge Deck Overlays, Field Performance Analysis", Report No. FHWA-0H-79-004, FHWA (1979).

15. Brown, R.A. "Monolithic Bridge Deck Experimental Cost Effective Restoration, Southwestern Blvd. S.H. 9269 (Route 20)", Initial Report, New York State Department of Transportation, 1978.

16. Babyak, R.C., "Monolithic Bridge Deck Experimental Cost Effective Restoration, Lake Street Over 684I", Initial Report, New York State Department of Transportation, 1977.

17. Hilton, N., "A Two-Inch Bonded Concrete Overlay for the Port Mann Bridge", Engineering Journal, May 1964, pp. 39-44.

18. Bergren, J.V. and Brown, B.C., "An Evaluation of Concrete Bridge Deck Resurfacing in Iowa", Special Report, Iowa State Highway Commission, 1975, 88 pp.

19. Brown, B.C., "A Further Evaluation of Concrete Bridge Deck Surfacing in Iowa", Special Report, Iowa Department of Transportation, 1979, 75 pp.

20. "Standard Test Method for Electrical Resistivity of Membrane-Pavement Systems" ANSI/ASTM D3633-77, American Society for Testing and Materials, Philadelphia, 1978.

21. Corkill, J.T., "A Field Study of the Performance of Bridge Deck Waterproofing Systems in Ontario", Proceedings of the 1975 RTAC Annual Conference. Vol. 2, 1975, pp. 79-100.

22. Chamberlin, W.P., Irwin, R.J. and Amsler, D.E., "Waterproofing Membranes for Bridge Deck Rehabilitation", Report No. FHWA-NY-77-59-1, Federal Highway Administration, 1977.

23. Stratfull, R.F., Jurkovich, W.J. and Spellman. D.L., "Corrosion Testing of Bridge Decks", Transportation Research Record 539, 1975, pp. 50-59.

24. Carroll, R.J., "Continuing Field Evaluation of Membrane Waterproofing for Concrete Bridge Decks", Report No. OHIO-DOT-20-77, Ohio Department of Transportation, 1977.

25. Fromm, H.J. and Wilson, G.P., "Cathodic Protection of Bridge Decks - A Study of Three Ontario Bridges ", Transportation Research Record No. 604, 1976, pp. 38-47.

26. Fromm, H.J., "Electrically Conductive Asphalt Mixes for the Cathodic Protection of Concrete Bridge Decks", Proceedings of the Association of Asphalt Paving Technologists, Vol. 45, 1976, pp. 382-399.

27. Fromm, H.J., "Examination and Reapplication of Cathodic Protection to the Duffins Creek Bridge", Internal Report, Research and Development Division, Ontario Ministry of Transportation and Communications, 1978.

28. Porter, J.C., "Precepts of the Evaluation of Facilities for Human Use and the Application to Bridge Replacement Priorities", Transportation Research Record 664, 1978, pp. 14-21.

29. Shirole', A.M. and Hill, J.J., "Systems Approach to Bridge Structure Rehabilitation or Replacement Decision Making", Transportation Research Record 664, 1978, pp. 22-31.

30. Shirole', A.M. and Hill, J.J., "Systems Approach to Bridge Structure Replacement - Priority Planning", Transportation Research Record 664, 1975, pp. 32-36.

31. Frascoia, R.I., "Vermont's Experience With Bridge Deck Protection Systems", 'Chloride Corrosion of Steel in Concrete', ASTM STP 629, D.E. Tonini and S.W. Dean Jr. Eds., American Society for Testing and Materials, 1977, pp. 69-81.

32. Hagen, M.G., "Bridge Deck Deterioration and Restoration", Investigation No. 639, Vol. 3, Minnesota Department of Transportation, 1978.

33. "Task Force on Durable Bridge Decks, Activities in 1976 and 1977", Ontario Ministry of Transportation and Communications, 1978, 60 pp.

TABLE 1: CORES FROM THE NITH RIVER BRIDGE

Core No.	Half Cell Potential Volts $Cu/CuSO_4$ 1975	1978	Core Delaminated
1	-0.49	-0.50	no
2	not recorded	-0.56	yes
3	-0.29	-0.30	no
4	-0.37	-0.54	yes
5	-0.23	-0.23	no
6	-0.42	-0.55	yes
7	not recorded	-0.54	no

TABLE 2: RELATIVE MERITS OF REHABILITATION METHODS

Rehabilitation Method	Advantages	Disadvantages
Concrete Overlay (Low-slump or latex modified concrete).	1. Structural component of deck slab. 2. Relatively impermeable. 3. Relatively long service life. 4. Well-suited to repair of badly spalled or scaled decks. 5. Many qualified contractors.	1. Not suited to decks with complex geometry. 2. Cannot bridge moving cracks. 3. Difficult to provide adequate texture on low slump concrete surface. 4. May not stop active corrosion.
Waterproofing Membrane with Bituminous Concrete Wearing Course	1. Bridge cracks with small amounts of movement. 2. Relatively impermeable. 3. Provides good riding surface. 4. Applicable to any deck geometry. 5. Many qualified contractors.	1. Performance highly variable. 2. Will not stop active corrosion. 3. Service life limited by wearing course. 4. Nonstructural component of deck slab. 5. Not suitable for grades in excess of 4 percent
Cathodic Protection	1. Stops active corrosion. 2. Can be used on decks with moving cracks. 3. Provides good riding surface. 4. Applicable to any deck geometry.	1. Presence of wearing course will accelerate deterioration of marginal quality concrete. 2. Nonstructural component of the deck slab. 3. Periodic monitoring of performance required. 4. Wearing course requires periodic replacement. 5. Specialized contractor and inspection required. 6. Electrical power source required.

TABLE 3: SCREENING OF REPAIR METHODS

Criterion	Concrete Overlay	Waterproofing Membrane and Paving	Cathodic Protection
1. Delamination and spalls exceeding 5% of the deck area.		No	No
2. Corrosion potentials in excess of -0.35 v over more than 20% of the deck area.		No	
3. Active cracks in deck slab.	No		
4. Remaining life of structure less than 10 years.	No		No
5. Concrete not properly air entrained.			No
6. Complex deck geometry. Skew exceeding 50° curvature exceeding 10° or changing super-elevation.	No*		
7. Limited load capacity of structure or span/thickness ratio of deck slab greater than 15.		No	No
8. Hydro unavailable.			No
9. Epoxy injection repairs previously performed and will not be removed.			No

* Restriction applies only to finishing machines having axis of screed transverse to axis of roadway.

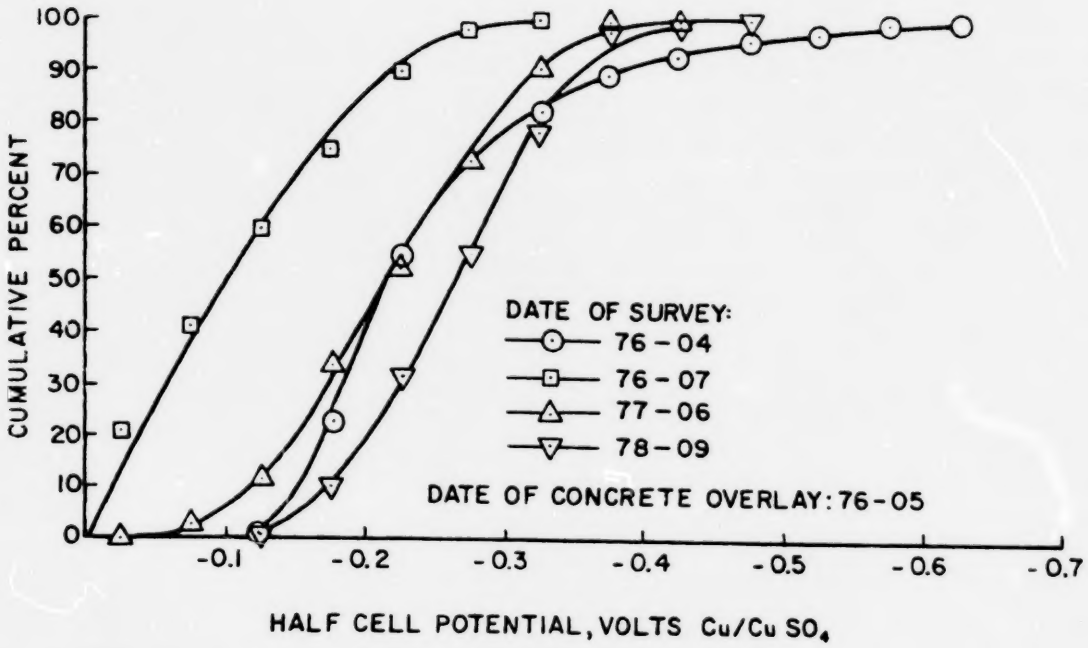

Figure 1: Site 06-232, I.C.4, Highway 401

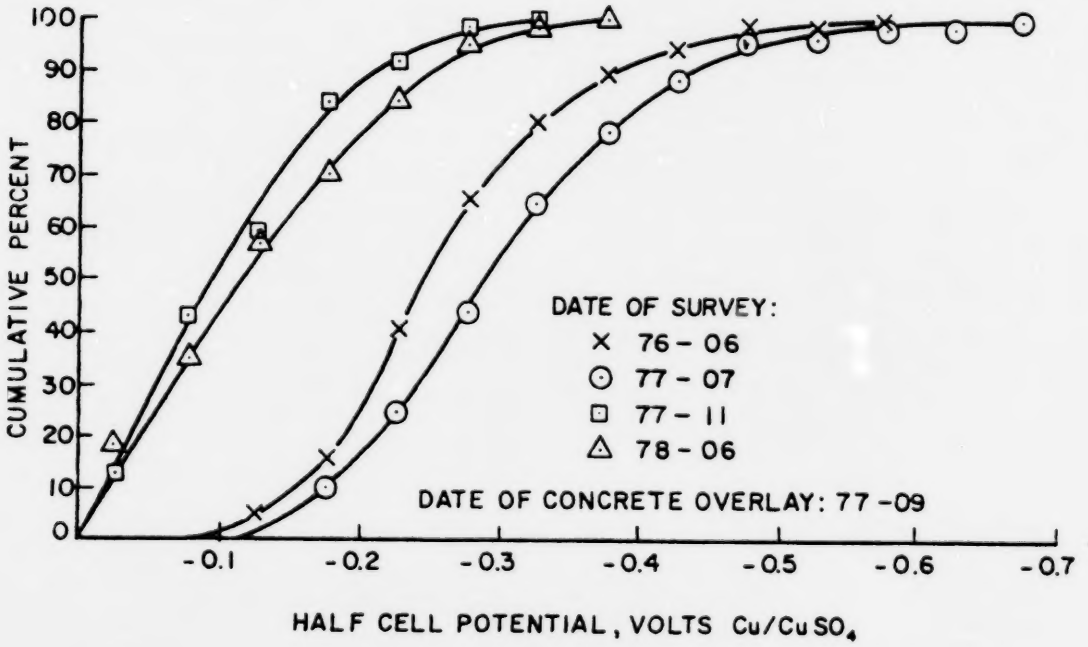

Figure 2: Site 47-002, Englehart River Bridge, Highway 66

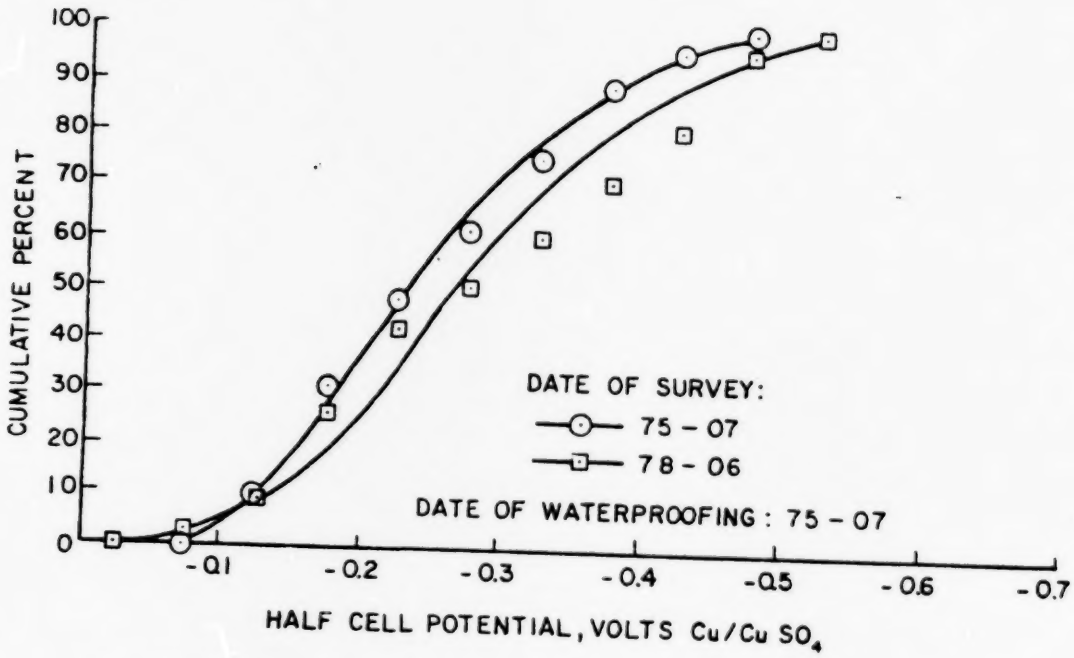

Figure 3: Site 23-124, Nith River. Highway 401

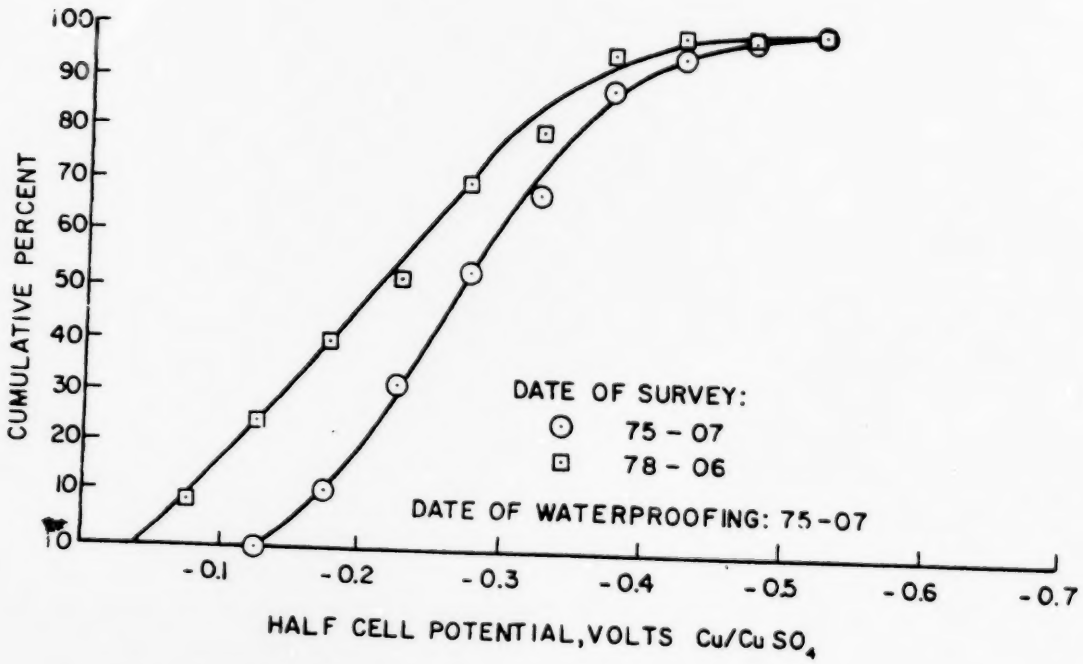

Figure 4: Site 23-118, C.P.R. Overhead, Highway 401